PHONON-PHONON INTERACTION IN CRYSTALS

FINAL REPORT
1 May 1960 - 17 February 1963

Signal Corps Contract No. DA-36-039-sc-87209
Order No. 39589-PM-61-91-91
PR and C No. 61-ELP\R-4122

Placed by U.S. Army Electronics Research
And Development Laboratory
Fort Monmouth, New Jersey

GENERAL ELECTRIC
HEAVY MILITARY ELECTRONICS DEPARTMENT
SYRACUSE · NEW YORK

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The objective of this project is to study the generation, propagation and interaction of phonons with emphasis on the phonon interactions in crystals.

Prepared for

U.S. ARMY ELECTRONICS RESEARCH AND
DEVELOPMENT LABORATORY
Fort Monmouth, New Jersey

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1. PURPOSE

The work performed under this contract is aimed at studying the generation, propagation and interaction of phonons in solids by means of microwaves. The main interest is centered on phonon-phonon interaction in crystals.

1.1 Task I Analytical Study

Investigate the generation and propagation of phonons in solids. Study the phonon interactions in one and three dimensional media.

1.2 Task II Experimental Study of Phonon Generation and Propagation

Investigate experimental techniques of generating phonons. Develop methods for enhancement of the transducer coupling. Evaluate the properties of phonon propagation in crystals.

1.3 Task III Experimental Study of Phonon Interactions

Study and evaluate the various types of phonon interactions in solids experimentally.

1.4 Task IV Material Evaluation

Measurement of the elastic properties of various materials and search for materials suitable for phonon propagation and interactions.

2. ABSTRACT

The object of this project is to study the generation, propagation and interaction of phonons with emphasis on the phonon interaction in crystals.

Phonon interactions have been interpreted as parametric interactions due to crystal anharmonicity. Several phonon-phonon interaction processes in X-cut quartz, <111> silicon and <100> germanium have been investigated. These involve forward traveling wave, backward traveling wave, frequency up conversion and harmonic generation studies.

Considerable analytical and experimental work has been done on the generation, detection, propagation and interaction of phonons. Theoretical curves based on the selection rules have been drawn for the various modes of operation for phonon-phonon interaction in solids.

Experimental results and observations are discussed pertaining to phonon generation and attenuation in various types of single crystals. Field enhancement techniques of microwave cavities for better microwave phonon generation have been utilized. Piezoelectric and magnetostrictive transducers and their characteristic behavior were analyzed. Geometries of the microwave structures are discussed.

Special attention has been given to evaluating possible methods of enhancing phonon interactions and improving the detection sensitivities of microwave phonons. A series of calculations was made for studying the feasibility of amplifying phonons in ruby by means of optically pumped phonon maser interactions. Tests were made on <110> GaAs involving electron phonon interaction at 1.1 kMc/s.

3. SUMMARY OF PUBLICATIONS, LECTURES, REPORTS AND CONFERENCES

10-27-61 "Broad Aspects of the Interaction in Parametric Devices," H. J. Evans & H. Hsu, 1961 IRE-PGED Conference, Washington, D.C.

11-2-61 "Parametric Interactions of Phonons," H. Hsu, Physics Department Colloquium, Syracuse University, Syracuse, N. Y.

11-20-61 Presentation at the U. S. Army Signal Research and Development Laboratory, Fort Monmouth, N. J., H. Hsu & S. Wanuga.

1-18-62 "Propagation of Elastic Waves in Crystals," H. Hsu, PGMTT, Syracuse Chapter, Syracuse, N. Y.

3-29-62 Presentation at the U.S. Army Signal Research and Development Laboratory, Fort Monmouth, New Jersey, H. Hsu and S. Wanuga.

2-28-62 A paper titled, "Three-dimensional Parametric Interactions of Waves and Quasi-particles," by Dr. H. Hsu was submitted for the correspondence section of the Proceedings of the IRE.

8-6/7/8-62 A conference was held at the Electronics Laboratory between W. G. Matthei, H. Hsu, and S. Wanuga to discuss the status of the project.

9-1962 A paper titled "Three Dimensional Parametric Interactions of Waves and Quasi-Particles," by Dr. H. Hsu was published in Proc. IRE.

11-28/29/30-62 A paper titled "Field Enhancement Techniques for the Generation of Microwave Phonons" was presented at the 1962 Ultrasonic Symposium at Columbia University. (Dr. H. Hsu, Dr. W. Brouillette and S. Wanuga).

6-29-62 A paper titled "Optical Pumping of Microwave Masers," by Dr. H. Hsu and Dr. K. F. Tittel was presented at the Electron Device Research Conference, University of Minnesota, and was published in Proc. IEEE, special issue on Quantum Electronics, January 1963.

11-20-62 A conference was held at the Electronics Laboratory between W. G. Matthei, S. Wanuga and W. Brouillette to discuss the status of the project.

11-30-62 A paper titled, "Field Enhancement Techniques for the Generation of Microwave Phonons," was presented at the 1962 Ultrasonic Symposium at Columbia University. (H. Hsu, W. Brouillette and S. Wanuga.) The paper has been submitted for publication in the forthcoming issue of PGUE of IRE Proceedings.

4. FACTUAL DATA

4.1 Phase I Theoretical Aspects

The study of phonon-phonon interactions in crystals is of course based on the theory of lattice waves, since the phonons are nothing more than the energy quanta stored in the various normal modes of the lattice vibrations. In the classical theory of specific heats, a detailed study is made of the various lattice vibrations in which thermal energy is stored, and by making suitable assumptions and going over to the quantum mechanical description, one arrives at the Einstein Debye theory of specific heats. In this treatment, it is assumed that the energy is distributed over the various modes in an equilibrium distribution, and one arrives at a description of the variation of specific heat with temperature without considering the detailed interchanges that take place in going from one equilibrium state to another.

The quantum treatment emphasizes the discreteness of the energy packets of quanta, and treats them like a statistical ensemble of individual particles very much like a gas. Collisions between the phonons explain the diffusion process which governs thermal conductivity. The original concept of normal modes is insufficient to describe this system, since the normal modes are predicated on linear oscillations that cannot interact. It suffices to point out that the normal modes were derived by considering the lattice energy to arise solely from quadratic terms in the lattice displacements. The presence of higher order terms gives rise to the anharmonic effects by which energy can be transferred from a mode at one frequency to a mode at another frequency. This is in every way analogous to the familiar non-linear mixing or heterodyning process so much used in communications.

Granting that a detailed description of lattice mechanics must take into account the effect of anharmonic terms, this can be effected by assuming a general solution of the equations of motion to be composed of perturbed solutions to the harmonic case in the usual manner. The quantum mechanical formulation gives a method for calculating the probability of a transition from one perturbed energy state to another, and a statement of the conditions that must be fulfilled for this to take place.

A phonon, or quantum of lattice energy, can be characterized by an energy $\hbar\omega$ and a wave vector $\vec{k}$. In the classical description, the corresponding wave entities are the frequency ω and the propagation constant β. Stated in quantum terms, the necessary conditions for a phonon-phonon interaction to occur are that the energy and momentum of the system before collision be conserved. The energy condition is on a scalar, the momentum condition on a vector. The concept of phonon momentum must take into account total lattice momentum, and for many phonon-phonon processes, the so-called Umklapp processes, one must invoke an interchange of momentum with a lattice to satisfy the momentum condition. This is somewhat analogous to an elastic particle bouncing off a rigid massive surface, where the particle reverses momentum but retains the same energy and the momentum imbalance is taken up by the rigid wall.

Stated in these terms, if a phonon of frequency ω_s and wave vector k_s interacts with a phonon of frequency ω_p and wave vector k_p, to form a resultant phonon of frequency ω_u and wave vector k_p, then the energy condition gives:

$$\hbar\omega_u = \hbar\omega_s + \hbar\omega_p$$

and the momentum condition gives, neglecting an Umklapp process:

$$\vec{k}_u = \vec{k}_s + \vec{k}_p$$

These are the conditions for a signal phonon and a pump phonon to combine to form a phonon having their joint energy and momentum. In the classical wave analysis, this is the process that leads to the upper sideband, where:

$$\omega_u = \omega_s + \omega_p$$
$$\beta_u = \beta_s + \beta_p$$

Once these conditions can be satisfied, the quantum theory calculates the probability of the joint transition using the transition matrix. The interaction probability is then the quantum formulation of the effects of non-linearity.

4.1.1 One-Dimensional Lattice Waves

In order to see how the conditions in 4.1 can be satisfied, it is necessary to examine the constraints which the lattice structure imposes on the energy and lattice vector of a given phonon. We consider cases where the interacting phonons or waves travel along the same path, although they may have opposite directions of travel. These are then plane waves, and can be discussed in terms of a one-dimensional wave equation. The lattice is composed of discrete lattice points. To a first approximation we can ignore the interactions between neighboring atoms more remote than nearest neighbors.

It may be true that the magnitude of the effects due to next-nearest neighbors is comparable to the magnitude of the anharmonic effects, but the interaction between two phonons of different frequency depends only on the anharmonic terms. The effect of the remoter neighbors changes the normal mode frequencies slightly and only affects the interaction in a higher order calculation. Thus, one can gain an understanding of the interaction process by considering only the forces on an atom due to its immediately adjacent neighbors, if one retains the higher order non-linear forces.

Since one deals here with one-dimensional waves, it is sufficient to consider a one-dimensional lattice consisting of a linear array of equidistant atoms with forces acting on each atom which are non-linear functions of the displacements between the given atom and its two nearest neighbor. The non-perturbed normal modes are derived by considering only the linear force terms, and the smaller non-linear terms are then treated as perturbations to these terms.

The displacement of an atom from its equilibrium position requires three components for a complete displacement, for there can be one longitudinal and two transverse displacements. Further, for an anisotropic medium, the transverse displacements can have two velocities of propagation. Most of the samples dealt with in this study were of such nature. The treatment of the one-dimensional lattice is well known. One of the clearest treatments is given in a book by Brillouin.[1] The essential features of interest are that each mode has cut-off frequencies which are determined by the lattice force constants and the particle mass, and that the construction of a compound lattice having two or more species of atoms introduces additional frequencies for which waves can be propagated. The equations are entirely analogous to the filter equations in communications networks. Considering only the lowest frequency branches of the three polarization modes, which are commonly known as the acoustic branches, there are upper cut-off frequencies, which occur at those frequencies where a lattice wave wavelength is just twice the distance between lattice points for the simplest lattice consisting of a single species of atom.

At frequencies which are a substantial fraction of the cut-off frequency, each branch exhibits dispersion, so that the relation between frequency and wave vector is not linear, the group velocity approaches zero at cut-off. The result of dispersion makes the determination of necessary frequency ratios for interaction quite cumbersome in the general case, and puts limitations on the general type of phonon-phonon interactions that can take place. However, the present study has to date only been concerned with frequencies up to 10 kMc/s , or 10^{11} cps, whereas the cut-off lies at about 10^{14} cps. For frequencies as far removed from cut-off as this, the dispersion curve relating frequency to wave vector is sensibly linear. The Heisenberg uncertainty principle allows one to estimate the deviations from the necessary conditions for interaction that can be tolerated, and the present case falls well within these limits.

4.1.2 Selection Rules for Phonon Interactions

In section 4.1 the necessary conditions for traveling wave interaction were discussed in terms of phonon energy and momentum. We recapitulate here in terms of frequency ω and propagation constant β for the one-dimensional case, where the vectorial significance of the momentum is exhibited by the algebraic sign of the propagation constant.

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(1) L. Brillouin, Wave Propagation in Periodic Structures, 2nd Edition, Dover, New York, (1953).

From the dispersion curves relating propagation constant and frequency, one can derive selection rules that conform to the conservation of energy and momentum. The anisotropy of most crystals results in three phonon branches for the acoustic modes, one longitudinal and two transverse. The general anisotropic treatment discloses that these wave components are not strictly transverse or longitudinal, but only approximately so, hence they are more properly referred as quasi-longitudinal and quasi-transverse modes.

Restating the general conditions for interaction,

$$\omega_p = \omega_s + \omega_i$$
$$\beta_p = \beta_s + \beta_i$$

The $\pm$ sign on β_s allows for forward and backward wave interactions respectively, the + sign referring to the forward wave case. In the present discussion, attention will be confined to the backward wave case by way of example, we rewrite the equations as:

$$\omega_p = \omega_s + \omega_i$$
$$\beta_p = -\beta_s + \beta_i$$

In Figure (1) we have sketched an ω-β diagram for an anisotropic crystal where there are three waves, a longitudinal, a fast transverse, and a slow transverse, with the allowed backward wave interactions. The pump frequency ω_p is greater than the signal frequency ω_s and the idler frequency ω_i . The small diagram indicates the general alignment of the segments representing the waves. The longitudinal branch is labelled T, the fast transverse T_f and the slow transverse branch is labelled T_s. By way of example, the transition marked I involves a

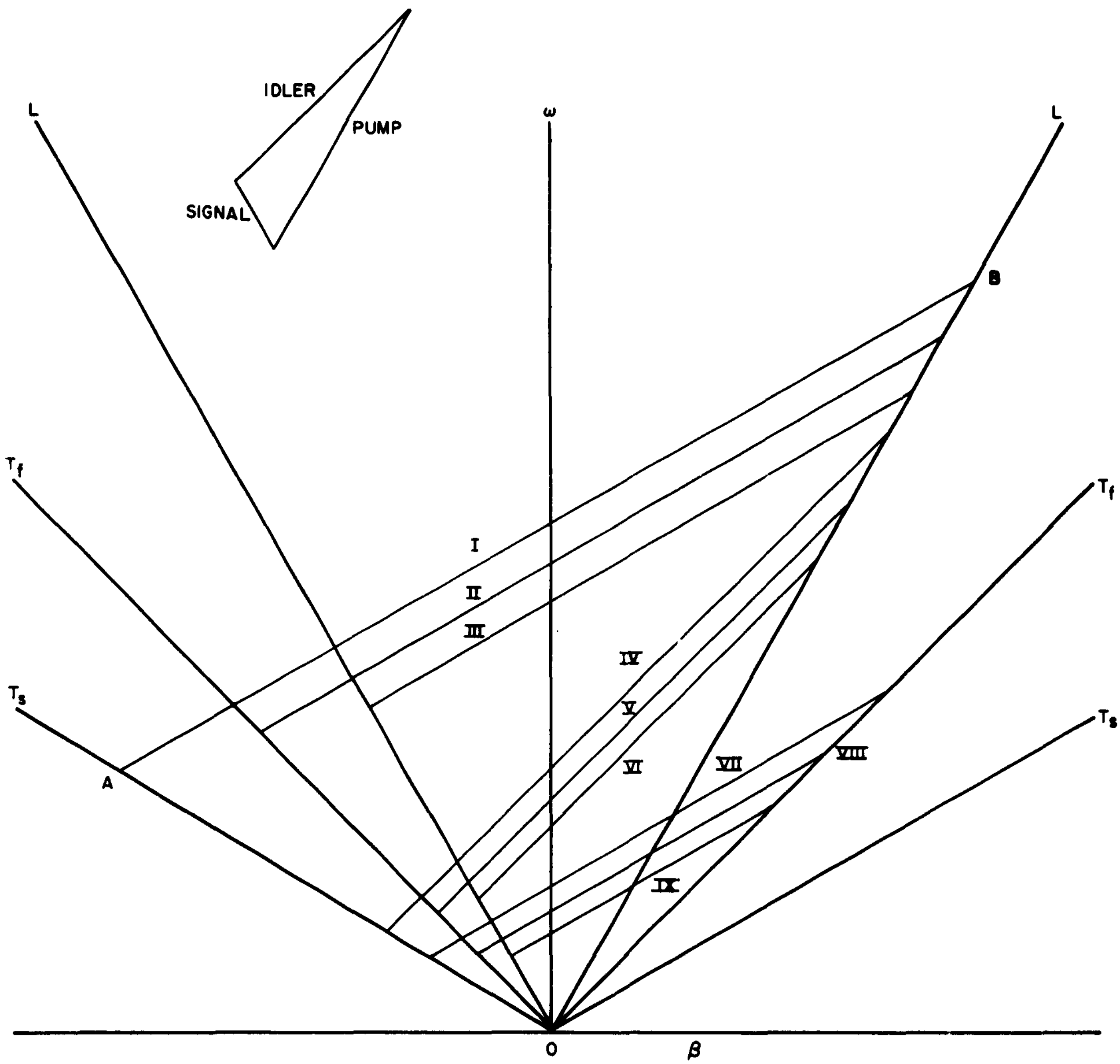

FIGURE 1

ω-β Diagram of Acoustic Lattice Waves in a Crystal, Showing Some Allowed Interactions.

pump wave on the longitudinal branch, a backward traveling signal wave which is slow transverse and an idler wave which is also slow transverse and traveling in the forward direction. The segment OA represents the signal, the segment OB the pump and the segment AB the idler. The ordinate of A represents the angular frequency of the signal, the ordinate of B the angular frequency of the pump wave, and the difference in the A and B ordinates the angular frequency of the idler. The abscissae of these points represent the propagation constants.

Each of the nine cases can be derived from the diagram, by observing that the three segments must form a closed triangle, and noting which modes can be used to do this. Thus we note that case I is for a longitudinal pump, slow transverse signal and slow transverse idler, II for a longitudinal pump, fast transverse signal and slow transverse idler, etc.

The specific selection rule we illustrate is deceptive. If we consider the phonons as particles, the case illustrated gives the conditions that a pump phonon must satisfy when it decays into two phonons of lower energy. The process in a backward wave amplifier involving this case must be a multi-stage interaction involving more than three phonons. A signal phonon and a pump phonon must interact in such manner as to induce the pump phonon to decompose itself into an idler phonon and an additional signal phonon, the final result being an idler phonon and two signal phonons. This higher order interaction may be less probable than a single up-conversion process.

4.1.3 Velocities in Crystals

The phase velocities of the longitudinal and transverse phonon waves are functions of direction of propagation and orientation of the particular crystal. The calculation and measurement of these velocities are used to determine the specific velocity ratio of various phonon waves in different propagating mediums. These values are in turn used to determine the selection rules of complex phonon modes for our study of phonon-phonon interactions, in particular for the backward wave type of interaction. Various crystals and crystal orientations have been used in our experimental testing and velocity measurements have been made for different materials and mumerous orientations. The following table is a brief summary of some of the single crystal materials measured:

	Quartz Trigonal		Ruby Trigonal	
Crystal Orientations	X	AC	BC	C
V_ℓ	5.75×10^5 cm/sec		6.4×10^5 cm/sec	11.2×10^5 cm/sec
V_{1t}	5.01×10^5 cm/sec	3.25×10^5 cm/sec		$V_{1t} = V_{2t}$ 6.25×10^5 cm/sec
V_{2t}	3.30×10^5 cm/sec	3.81×10^5 cm/sec	5.2×10^5 cm/sec	

	CdS Hexagonal	KDP Tetragonal
Crystal Orientation	C	C
V_ℓ	4.54×10^5 cm/sec.	3.8×10^5 cm/sec.
$V_{1t} = V_{2t}$	1.76×10^5 cm/sec.	

	Silicon-Diamond	Germanium-Diamond
Crystal Orientation	⟨111⟩	⟨100⟩
V_ℓ	9.69×10^5 cm/sec.	4.89×10^5 cm/sec.
$V_{1t} = V_{2t}$	5.12×10^5 cm/sec.	3.56×10^5 cm/sec.

	Gallium Arsenide Sphalerite
Crystal Orientation	⟨110⟩
V_ℓ	5.5×10^5 cm/sec.
V_{1t}	3.56×10^5 cm/sec.
V_{2t}	2.6×10^5 cm/sec.

These velocity measurements were made at frequencies ranging from 1 kMc/s to 10 kMc/s for the quartz, 3 kMc for the ruby, 1 to 3 kMc/s for the Si and Ge, 1 kMc/s for the GaAs, 10 Mc and 1 kMc/s for the CdS and 17 Mc for the KDP. No attempts were made to measure the velocities to extreme accuracies, and the figures possibly contain some slight error due to equipment calibration.

4.2 Traveling Wave Phonon Interactions

Parametric interactions can be interpreted as a consequence of anharmonic potentials. In our first quarterly progress report, parametric interactions of phonons due to the presence of deformation potentials have been considered. Various types of traveling wave parametric interactions are possible which may be used for possible experimental verification. The following sections briefly describe some of the processes we have considered.

4.2.1 Frequency Conversion

We now consider two waves of different frequency propagated independently. Let the frequencies be known as (pump) ω_p with phase constants B_p and (signal) ωs with phase constant Bs. Solutions of the equations of motion are of the form $Y_n = Ae^{j(Bx - \omega t)}$ for a one dimensional case propagating in the X direction. The sum or difference frequencies of the original waves are called combination frequencies, ie, $(\omega p + \omega s) - \omega\mu$ and $(\omega p - \omega s) = \omega_\ell$, where $\omega\,\mu$ corresponds to the upper or sum frequency and ω the lower or difference frequency. The corresponding phase constants are $B\mu$ and B . Thus the superposition of two waves with values ωp, Bp and ωs, Bs can lead to a sum frequency $\omega\,\mu$, $B\mu$ due to lattice anharmonic effects. The corresponding relations are then

$$\omega\,\mu = \omega p + \omega s$$
$$B\mu = Bp + Bs$$

$$\omega_\ell = \omega p - \omega s$$

$$B_\ell = Bp - Bs$$

If the energy of the waves Bp and Bs travels in the same direction, then interaction is possible if all three waves are longitudinal or all three are transverse, since the frequencies we deal with are so low that the dispersive effect of the lattice may be ignored.

We have been mainly interested in searching for upper sideband frequency conversion since this offers ease in experimental procedures and involves only a one-step process, that is a pump and signal phonon wave combining to create a single phonon of higher energy. If interaction should occur with up-conversion, then the signal should show an increased attenuation with the addition of a pump wave and energy should appear at the sum frequency. This process would give direct observation of phonon-phonon interaction in solids.

4.2.2 Harmonic Frequencies

The nonlinear effects in the lattice would also generate harmonics of a wave if the disturbance of the lattice is great enough to produce a large nonlinearity. Therefore, if a single frequency ωp, Bp traveling wave of large amplitude is propagated in a solid, harmonics of the form $2\,\omega p$, $2\,Bp$, $3\,\omega p$, $3\,Bp$, etc., would be generated due to the nonlinearity of the medium. In this case the equations of motions would contain terms of the form $e^{2j(Bpx\ -\ \omega pt)}$, $e^{3j(Bpx\ -\ \omega pt)}$, etc. Therefore, evidence of any of these harmonics would in effect produce a measure of the nonlinearity present. It is to be noted that harmonics of this large amplitude pump wave would be present in all the types of interactions being investigated, the frequency conversion already discussed and also the forward and backward traveling wave interactions to be discussed later. The presence of harmonics in these cases can be somewhat detrimental since energy is extracted from the pump frequency wave as it propagates and less interaction with the signal wave takes place, due to the lower pump energy available.

4.2.3 Forward Traveling Wave Interaction

The forward traveling wave type of interaction involves three frequencies in which:

$$Wp = Ws + Wi$$

$$Bp = Bs + Bi$$

where Wp, Ws and Wi are the pump signal and idler frequencies respectively and Bp, Bs and Bi are the phase propagation constants of these same waves. The idler wave Wi is a by-product of the pump and signal waves. To achieve proper operation the traveling waves at the pump, signal and idler frequencies are required to have proper phase relations.

Phonon-phonon interactions encountering gain of the signal wave are higher order processes involving the creation of two phonons, one at the idler frequency and one at the signal frequency. The simplest type of forward type of traveling wave interaction is that in which all three phonon waves are collinear. This can be described as one where all three waves are of the same mode, longitudinal or transverse. The more complicated cases involve the use of different wave modes. The pump wave could then be a longitudinal wave and the signal and idler transverse waves. The latter case although more complicated could be derived by using the equations of parametric interactions for finding coupled phonon normal modes.

Forward traveling wave types of phonon interactions with gain for the signal wave can, therefore, be described as processes due to the nonlinearity of the medium where two waves combine to form a by-product (ω_1) which in turn adds energy to the signal wave. This parametric interaction involving gain at the signal frequency may be lessened by losses due to energy transfer of the signal wave to the sum frequency described in section 4.2.1. In that section it was shown that a pump and signal wave may combine to form an upper sideband frequency. Therefore, although some gain of the signal may be achieved, it may not be significant, since more energy may be transferred to the upper sideband frequency. Harmonics of the pump frequency are also undesirable since energy is extracted from the main pump signal, thereby lowering the effective pumping power. These problems exist in both the forward and backward (to be described in the next section) traveling wave type of interactions. It would, therefore, be desirable to achieve some means of suppressing these energy transfers of higher order harmonics and sum frequencies if possible.

4.2.4 Backward Traveling Wave Interactions

The backward traveling wave case is based upon our studies of parametric interactions in nonlinear periodic structures. These concepts were subjected to experimental tests with microwave parametric amplifiers.(2) The main characteristics of the backward traveling type of interactions as witnessed in the electromagnetic parametric case are wide tuning range and inherent regeneration with the possibility of oscillations.

In the case of phonon interactions in solids, this type of interaction must be interpreted as a multi-phonon process. The equations describing backward traveling wave type of interactions can be represented as follows:

$$Wp = Ws + Wi \qquad (1)$$

$$Bp = -Bs + Bi \qquad (2)$$

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(2) H. Hsu, "Backward Traveling-wave Parametric Amplifiers," paper presented at 1960 International Solid-State Circuits Conference, Philadelphia, Penn., and International Congress on Microwave Tubes, Munich, Germany, 1960.

The procedure describing phonon-phonon interactions may be given by:

$$Ep = Es + Ei$$

since the ratio of the energy is equal to the ratio of the corresponding frequencies of the phonons. In Figure (2) equations (1) and (2) are plotted in terms of the ratio of the phase velocities, v_p, v_i and v_s corresponding to Wp, Wi and Ws respectively. The various phase velocities correspond to the velocities of longitudinal or transverse phonon waves. The figure shows the corresponding ratios of the frequency and phase constant for one particular operating condition. The procedure can be extended to more complicated scattering processes.

4.3 Optically Pumped Phonon-Maser Interactions in Ruby

Devor(3) et al have demonstrated maser action in ruby by pumping a ruby crystal using coherent light emitted by a second ruby operating as a laser. This established the possibility experimentally of pumping a ruby crystal with optical photons to achieve population inversion of the ground state coublet of Cr^{+++} ions in ruby.

Tucker(4) of the General Electric Research Laboratory has previously demonstrated spin-phonon maser action in the same crystal system using microwave energy to achieve population inversion in the ground state. In Tucker's experiment, the ground state spin system of a suitably oriented ruby crystal in a magnetic field was energized by pumping with microwave energy at 23.3 kMc/s to invert the population of the spin system levels. An injected phonon wave at 9.3 kMc/s then interacted with the spin system with consequent amplification of the acoustic wave.

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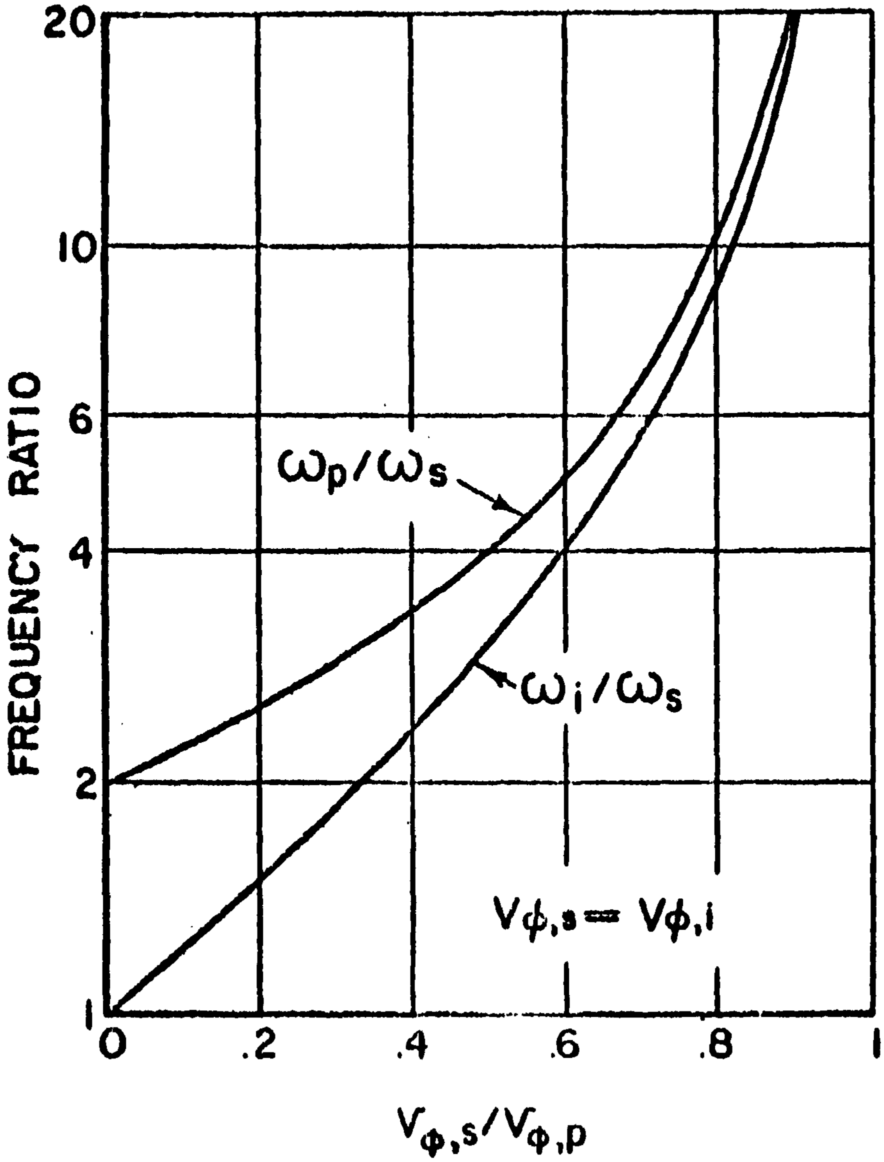
(3) D. P. Devor, I. J. D'Haenens, and C. K. Asawa, Phys. Rev. Letters, 8, 432, (1962).

(4) E. B. Tucker, Phys. Rev. Letters, 6, 547, (1961).



FREQUENCY RATIO vs. VELOCITY RATIO WITH NO DISPERSION FOR SIGNAL AND IDLER WAVES

FIGURE 2

In the Devor experiment, the ruby system was pumped with photons that achieve the same population inversion in the same crystal. The ruby crystal then observed to oscillate in a maser mode at 22.4 kMc/s.

The above experiments were performed at liquid helium temperature, 4.2° K. Calculations have been made and indicate that it should be possible to extend this temperature upward to liquid nitrogen temperature and still secure a reasonable pump efficiency using optical pumping. For a complete description of calculations and results, the reader is referred to the interim and 5th quarterly progress reports of this contract. In Tucker's experiment, a gain for the phonon wave of .12 per cm. was obtained. Although phonon attenuation is higher at liquid nitrogen temperature, we have been able to observe phonons in ruby at 3 kMc/s at this temperature, so that it should be feasible to work in this range. An energy diagram for this system is contained in Figure (3). The unperturbed states of the Cr^{++} ion in ruby are split by the action of the magnetic field on the spins. The transition AB represents the energy of an optical photon emitted by an unperturbed ruby acting as a laser. The transition A'B' represents the same energy difference in the presence of a magnetic field, and the system can be pumped at this point by using an optical laser. The transition CD is the microwave difference energy that corresponds to the necessary energy to interact with the phonon wave to yield phonon amplification.

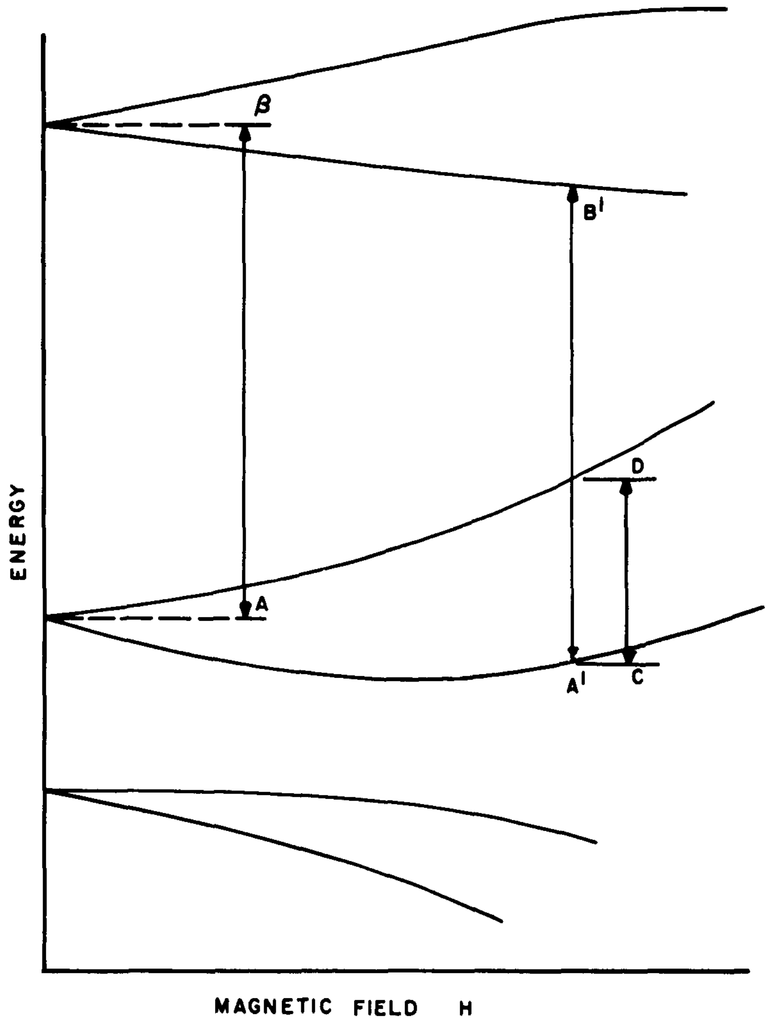


Figure 3. Energy Diagram for State Splitting in Ruby

4.4 Phase II Experimental Studies

4.4.1 General Considerations

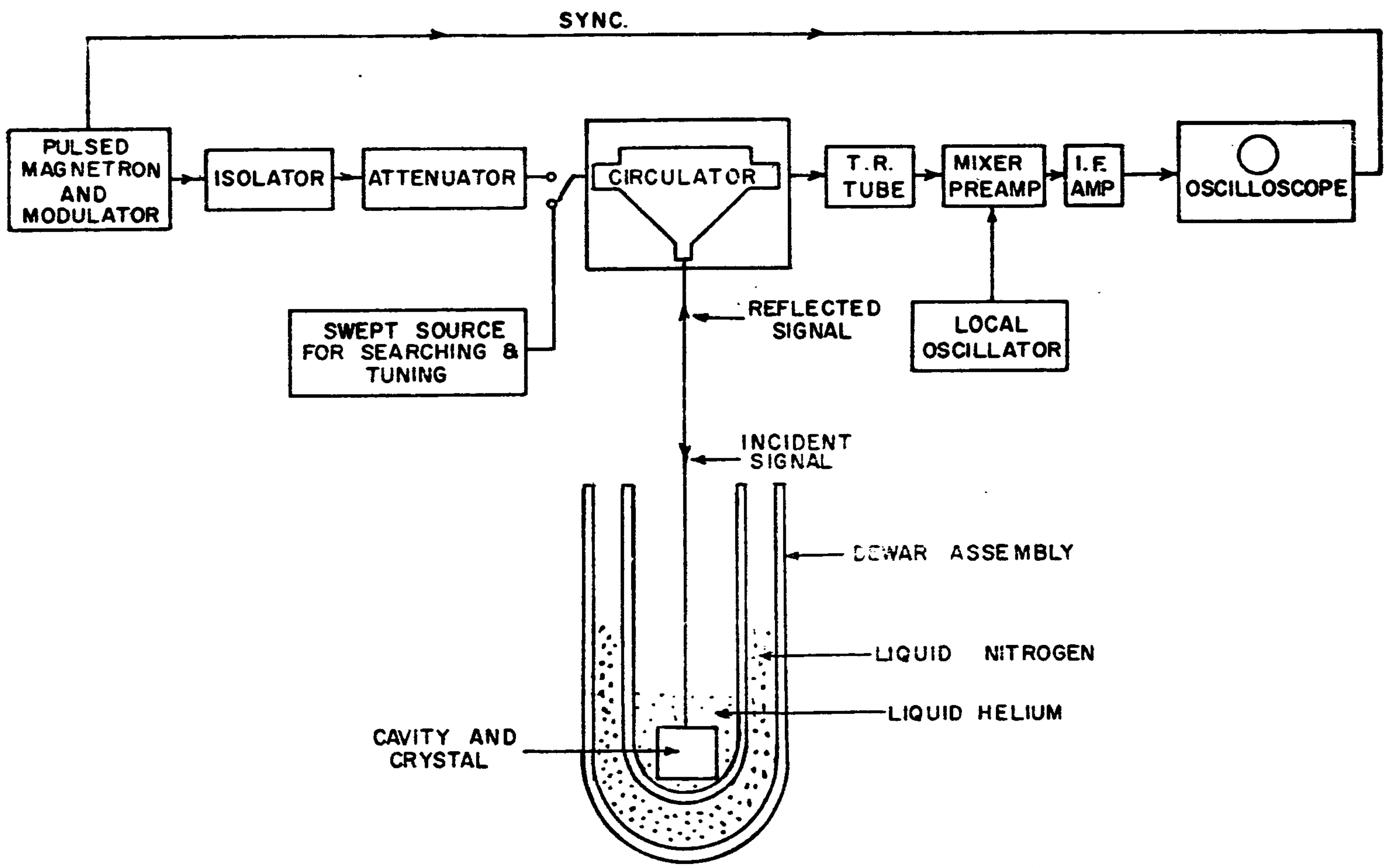
As mentioned previously, several types of traveling wave interactions are possible for phonon waves insolids. The forward traveling wave interaction involving excitation of all waves with identical velocity of propagation is believed not to be a strong interaction process. However, this case does offer a useful detection means for studying the various phonon interactions that have been proposed, but have not as yet been verified experimentally. The backward traveling wave type of interaction is one which is of particular interest. It is expected that with a crystal of about 1 cm. length, it may be possible to achieve strong interaction if the fraction of the anharmonic component of the potential reaches the order of 10^{-5}. There are numerous modes of operation for this type of interaction depending upon the chosen mode of operation. Both the forward and backward traveling wave type of interaction involve higher order or multi-phonon processes, whereas harmonic generation and upper frequency conversion are of the single order type. Therefore, it appears reasonable to assume that the harmonic generation and upper frequency conversion cases would be the more likely to succeed in order to verify phonon interactions experimentally. However, all four processes have been attempted in our experimental testing.

All the experimental work was designed for investigating microwave phonon generation, detection and propagation in various types of crystal mediums. The equipment had been designed to include studying the various types of phonon interactions that have been proposed. Due to limited space in the cryogenic facilities, consideration was given in all microwave structures to keeping them small. The structure must also be of small volume in order to reduce the necessary amount of liquid helium coolant. Materials with low thermal conductivity such as stainless steel have been used for microwave input and output structures in order to reduce heat transfer to the inside of the dewar.

Since we are attempting to study various types of crystals and different orientations of crystals, numerous cavities must be built whose frequencies will depend upon the velocities of propagation of the particular material, especially for the backward traveling wave case. The cavity structures are designed to include external mechanical tuning of the resonant frequency. The reason for this is that the cavity frequency will shift when it is immersed in liquid helium or nitrogen. This change is due to both the coefficient of expansion of the materials and the dielectric constant of the liquid. Another reason is that with external tuning we are able to achieve the proper frequency ratio more easily for our backward traveling wave interaction study.

The microwave energy sources used for phonon excitation have consisted primarily of pulsed magnetrons at S and X-band frequencies. These magnetrons have a pulse width of about 1 μ sec. and power ratings of 50 watt CW and 5 KW peak power for the S-band and 5 to 50 KW peak power for the X-band. Electronically tunable CW BWO tubes of power ratings of about 200 watts average power are also incorporated with pulse modulation. L-band BWO tubes with pulse modulation, delivering about 2 watts peak power are also used. Various types of 3 port circulators, isolators, TR tubes and low noise I.F. amplifier detection systems were used to complete the microwave circuit assembly. The frequency range of operation is somewhat reduced by these components due to their narrow pass band. However, various combinations of different components usually overcome this slight disadvantage.

Figure (4) shows a sketch of a complete assembly using a cryogenic dewar unit and microwave circuitry for various phonon experiments. The microwave circuitry consists of a pulsed microwave magnetron, ferrite isolator, 3-port circulator, microwave cavity assembly, TR switch, low noise I.F. detection system and a cathode ray oscilloscope. The portable cryogenic unit consists of a double dewar assembly. The outer jacket dewar contains liquid nitrogen while the inner dewar contains liquid helium. The dewar assembly is mounted on a portable table with a pressure regulator system used for controlling gas pressures when transferring liquid coolant. Typical operation with the pulse echo technique using a quartz crystal is as follows: A microwave pulse of 1 μsec. width passes through the ferrite isolator and is coupled through the circulator to the re-entrant type cavity which is tuned to the same frequency as the magnetron. The quartz rod is located in a region of high R.F. field intensity in the cavity. The pulsed oscillating electric field is impressed normal to one face of the quartz crystal and piezoelectrically initiates a sound wave which propagates along the axis of the crystal. As the wave arrives at the opposite end, it is reflected at the crystal surface and returns to the original end face of the crystal. Upon returning to the original end face, part of the energy is reconverted back to an electromagnetic field and the remaining portion



SKETCH OF COMPLETE EXPERIMENTAL ASSEMBLY USED FOR MICROWAVE PHONON TESTING

FIGURE 4

is once again bounced back and forth between the end faces of the crystal. The delay time between each successive pulse will depend on the length of the crystal and the sonic velocity of the particular material and crystal orientation being used. Since in this case we are using one cavity and observing the reflected signal, the effective length of the crystal will be 2ℓ where ℓ is the length of the crystal. This reflected signal then passes through port number three of the circulator on to the TR tube. The low level signal is detected and amplified by a low noise mixer and I. F. receiver combination and is then displayed on the oscilloscope.

4.5 Materials

Experimental work was initiated using quartz crystals primarily because of the previous work on single frequency phonon propagation[5] in this material. Quartz has also been used as the transducer for the excitation of phonon waves when non piezoelectric propagating media were used. Quartz cuts of different orientations were used in many experiments involving the study of generation, propagation detection and phonon interaction.

There are several indications that germanium and silicon may be suitable for phonon interaction applications. Palevsky, et al[6] indicated that "for Si, as well as Ge, there are long-range forces present." R. N. Hall[7] has observed phonon-phonon interactions (creation) of transverse phonons in tunnel diodes. The Brown University group has observed strong thermal

(5) E. H. Jacobsen, "Experiments with Phonons at Microwave Frequencies," paper in Quantum Electronics, edited by C.H. Townes, Columbia University Press, New York, (1960). H. E. Bommel and K. Dransfield, Phys. Rev., 117, 1245, (1960).

(6) H. Palevsky, D. J. Hugjes, W. Kley, and E. Tunkels, Phys. Rev. Letters, 2, 258, (1959).

(7) R. N. Hall, G. E. Research Laboratory Report 60-RL-2509.

phonon-phonon interactions in the 50° K range.[8] Verma and Joski[9] have proved that the heypesonic attenuation in germanium observed by the Brown University group[8] is due to Umklapp process.

Germanium and silicon single crystals of low impurity were kindly supplied by Dr. Dave Hartman of Semiconductor Products Department, General Electric Company. These crystals were tested at various frequencies and temperatures in our phonon interaction studies.

As other materials became available they were also used in our studies. Materials studied were ruby, gallium arsenide, cadmium sulfide and KDP.

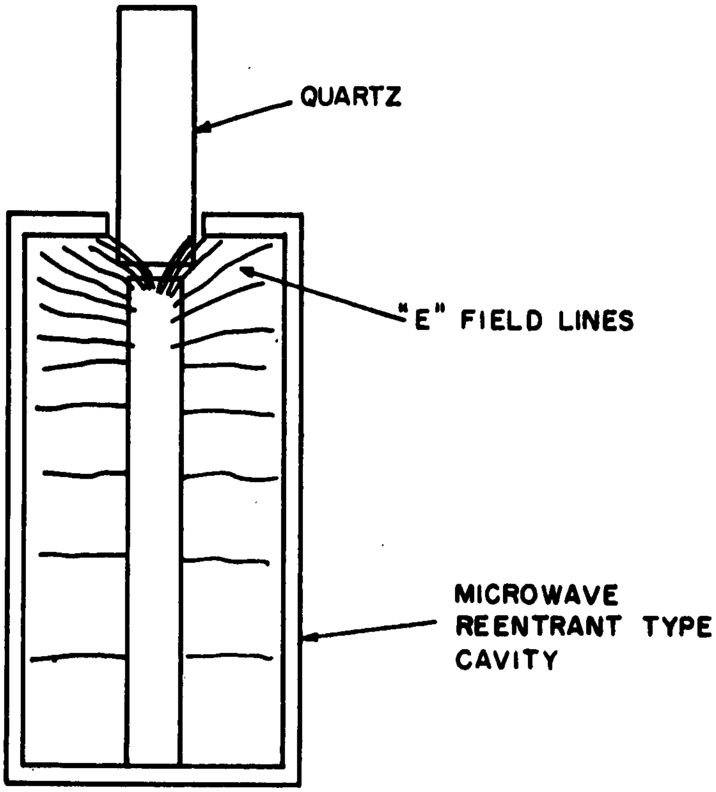
All transducers and propagating material require stringent optical tolerances for operating at microwave frequencies. The ends must be optically flat, to 1/20 wavelength of light, parallel to 0.001 degrees and normal to the crystal axis to within 0.01 degrees. Any change in flatness or parallelism will interfere with proper propagation.

4.6 Experimental Results

4.6.1 Generation of Phonons

Generation and detection of phonons is normally accomplished by using a piezoelectric transducer such as quartz for converting electrical energy into mechanical energy by means of the piezoelectric effect. If the propagating material be quartz, then no addition transducer is required in certain directions of propagation since a finite portion of the edge of quartz acts as the transducer and the rest of the rod as the propagating medium. An oscillating R.F. electric field is applied to a suitable face of a quartz crystal with the result that a mechanical elastic wave is generated equal to that of the R.F. field. Figure (5) shows a sketch of utilizing

(8) E. R. Dobbs, B.B. Chick, and R. Truell, Phys. Rev. Letters, 3,332,(1959).
(9) G. S. Verma and S. K. Joshi, Phys. Rev., 121, 396, (1961).



METHOD USED FOR PIEZOELECTRIC GENERATION
OF PHONONS

FIGURE 5

piezoelectric generation in a microwave cavity. The chosen axis of the rod is dependent on the method of wave propagation desired. For example the X-cut rod is a pure mode axis for both longitudinal and transverse waves. The Y-cut is pure for only longitudinal waves. There are many other cuts - AC, BC, etc., each having certain characteristics of wave propagation. Thin quartz slices of these cuts may be bonded to any material for generating sound waves. The bonding problem at microwave frequencies becomes extremely critical since bond thicknesses must be made comparable to 1/2 wavelength, approximately 5,000 Angstroms at X-band.

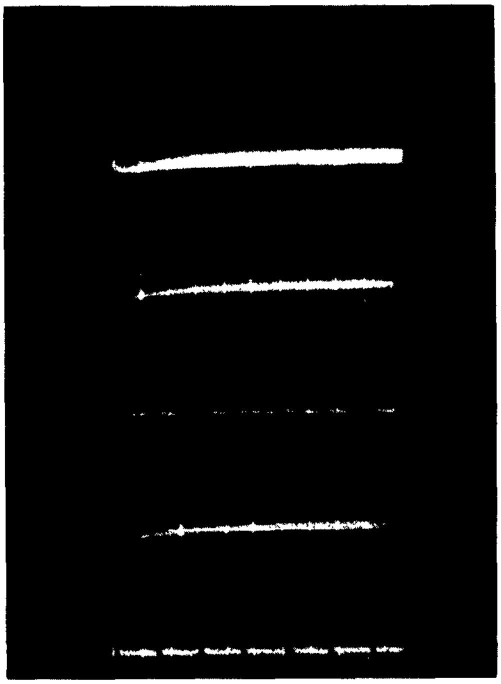
One of the basic problems in phonon experiments is the relatively low electromechanic coupling of the transducer, being of the order of about 9 per cent in quartz. For any phonon device to achieve practical value, improvement in the transducer coupling is one of the most important conditions. One aspect of our effort to improve transducer coupling was to evaluate the various methods of bonding transducers. Thin layers of evaporated indium, lead and gallium, as well as nonaq, stopcock grease and Dow Corning silicon fluid 200 series have been attempted. Of these, the silicon fluid and Nonaq have been most successful.

Another approach for improvement of transducer coupling has been to enhance the coupling field in the microwave cavity. Various cavity structures were designed, in which the field was measured by means of perturbation methods. With the E field enhanced cavity structure, far better phonon excitation has been achieved.[10] Figure (6) shows the simultaneous generation of both longitudinal and transverse waves in an X-cut rod using our E-field enhanced structure. Figure (6a) shows the full

(10) H. Hsu, W. Brouillette and S. Wanuga, "Field Enhancement Techniques for the Generation of Microwave Phonons," presented at 1962 Ultrasonics Symposium, Columbia University. To be published in the forthcoming issue of PGUE.

echo pattern of both longitudinal and transverse modes. Figure (6c) shows the expanded portion of echo pattern displayed by the marker in Figure (6b) which corresponds to about 1 millisecond delay time. Both longitudinal and transverse modes are easily recognized in (6c). Figure (6e) shows the expanded portion of echo pattern displayed by the marker (6d). The delay time is about 2.4 milliseconds. Only the transverse mode is present. The number of longitudinal echoes is about 180. The corresponding total storage time is about 1.5 milliseconds. The number of transverse echoes observed is about 340. The corresponding storage time is about 5 milliseconds. The crystal used was a 6 mm. diameter by 2.5 cm. length X-cut quartz.

Another means of generating and detecting microwave phonon waves is by means of magnetostriction. In this method a thin film of magnetostrictive material is plated on the end face of a crystal and the filmed edge is then inserted in a microwave cavity near the region of a high r.f. magnetic field. An external d.c. magnetic field is then applied in various orientations with respect to the film. Figure (7) shows a sketch of this type of operation. This type of transducer has been very successful. The advantage of using a thin magnetostrictive film lies in the fact that the geometry of the propagating medium stands very little chance of being changed. The added problem of bonding which occurs in the piezo-case is thus removed. Figure (8) shows an echo pattern displayed by using magnetostrictive excitation of phonon waves in an X-cut quartz crystal.



2-a I MILLISEC. / CM. SWEEP

2-b MARKER SHOWING ABOUT I MILLISEC DELAYED SWEEP FOR EXPANDED DISPLAY OF 2-c

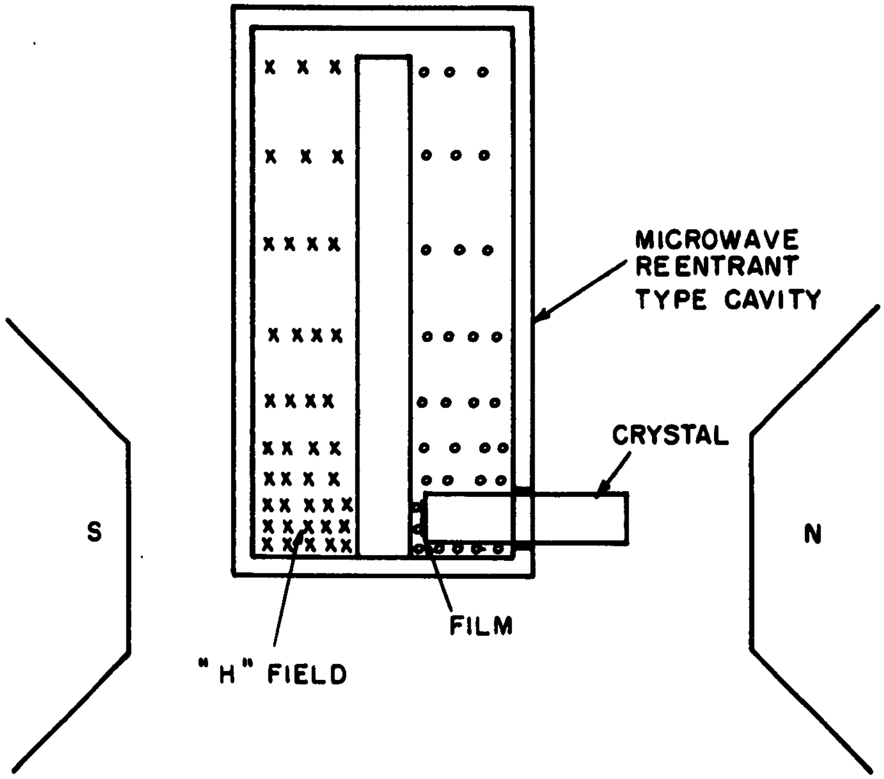
2-c EXPANDED SWEEP AT 10μ sec./cm.

2-d MARKER SHOWING ABOUT 2.4 MILLISEC DELAYED SWEEP FOR EXPANDED DISPLAY OF 2-e

2-e EXPANDED SWEEP AT 10μ sec./cm.

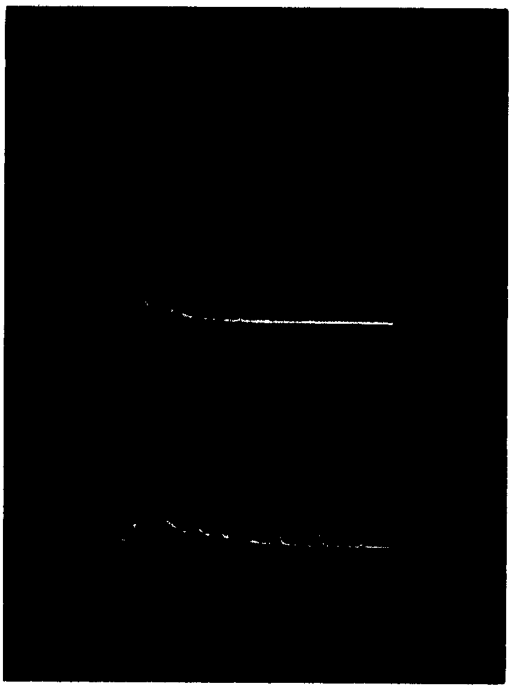
SIMULTANEOUS GENERATION OF LONGITUDINAL AND TRANSVERSE MODES IN X CUT QUARTZ, FREQUENCY 2.58 KMC/S

FIGURE 6



METHOD USED FOR MAGNETOSTRICTIVE
GENERATION OF PHONONS

FIGURE 7



10 usec/cm.

5 usec/cm.

Figure 8. Slow and Fast Transverse Mode Echoes in X-cut Quartz, Magnetostrictive Excitation, Biasing Field Applied, 1.15 kMc/s - Room Temperature

The coupling of magnetostrictive film excitation is largely dependent on the biasing DC magnetic field orientation and field strength. The effects associated with generation and propagation using thin films of magnetostrictive materials was studied while experimenting with these types of transducers. With the DC magnetic field applied normal to the film, transverse waves are generated. For other orientations of the field, the longitudinal mode is coupled. It was found that the longitudinal mode requires lower applied field strength than the transverse mode. The longitudinal mode, therefore, appears more promising for phonon interaction studies where more than one frequency is involved.

4.6.2 Phonon Propagation in Quartz

Several different orientations of quartz crystals were investigated. X-cut quartz rods were used mainly because this particular cut offers pure mode axes for the longitudinal and transverse waves. Both piezoelectric and magnetostrictive transducer excitation was used throughout. Figure (5) has already shown phonon propagation in X-cut quartz using piezoelectric excitation. Figure (9) shows a longitudinal mode in X-cut quartz. The flatness of the echo pattern is due to saturation of the receiver. Figure (10) shows the pattern of echoes observed in X-cut quartz using a modified microwave cavity structure in an attempt to enhance the transverse mode. About 6 milliseconds of storage time is displayed for this mode.

Figure (11) shows the results obtained in a test for obtaining some values of attenuation in single crystal quartz. The measurements were made at 2.93 kMc/s and liquid helium temperatures. An attenuation

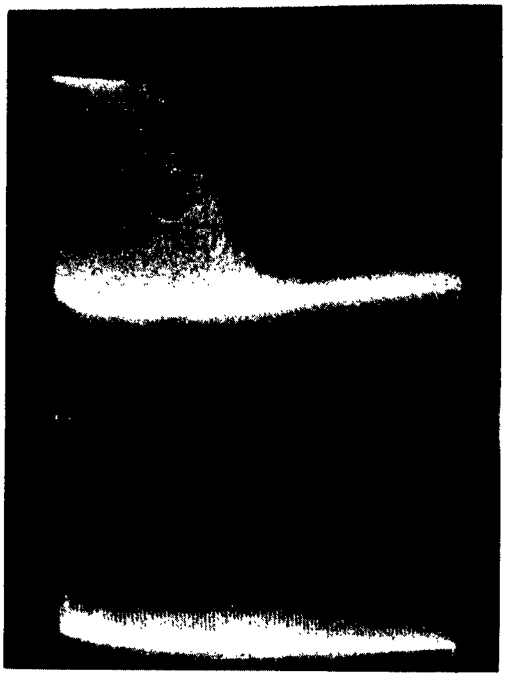


Figure 9. Longitudinal Mode Echoes in X-cut Quartz, Approximately 180 Echoes at 9.3 kMc/s

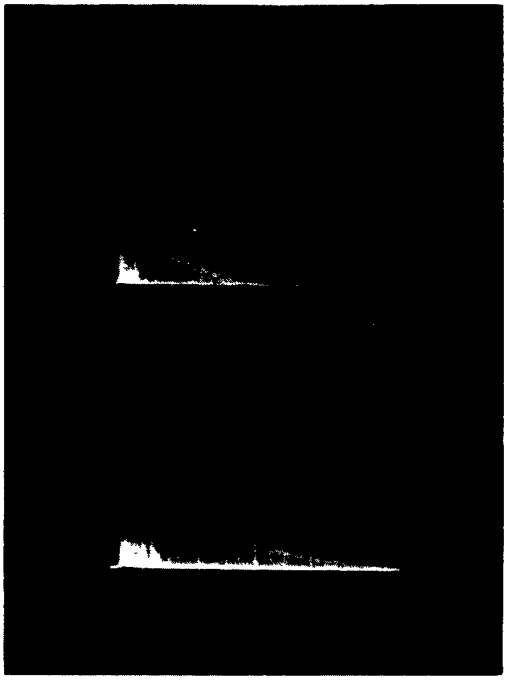
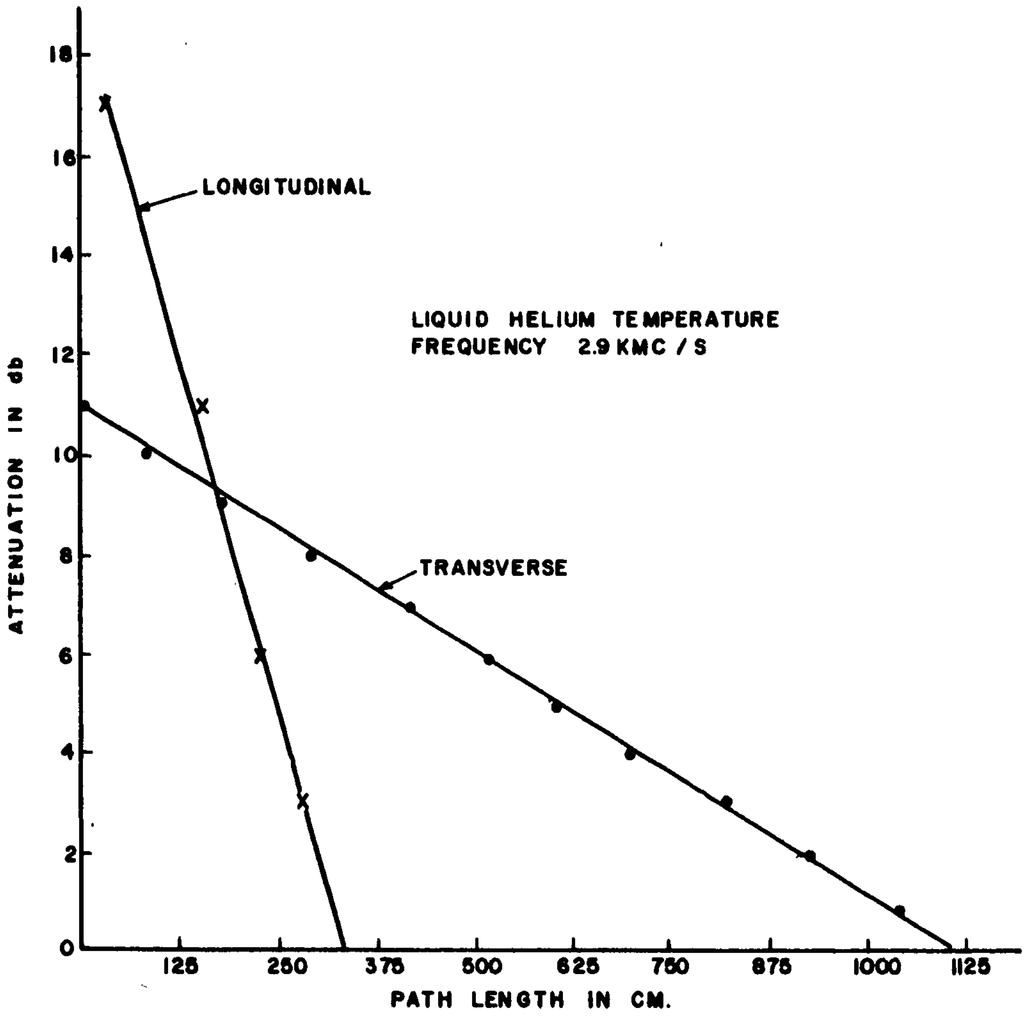


Figure 10. 3.3 kMc/s Transverse Mode Echoes in X-cut Quartz Using Enhanced "E" Field Structure



ATTENUATION IN X-CUT QUARTZ AT LIQUID HELIUM TEMPERATURE

FIGURE 11

of approximately 0.06 db/cm was measured for the longitudinal mode in an X-cut quartz rod, 6 mm. diameter by 2.5 cm. length. A value of approximately 0.01 db/cm. was obtained for the slower transverse mode in an X-cut quartz rod 6 mm. dia. by 3 cm. length.

Cuts of AC and BC quartz rods 3 mm. in diameter by 2 cm. length were also tested. These two cuts are of interest since they are the only two orientations of rotated Y-cuts where transverse waves have no cross coupling to other modes. The acoustic energy travels parallel to the normal of the wave fronts.

The AC-cut rod is made by a rotation about the X-axis of 31° with respect to the Z-axis. The BC-cut crystal is made by a rotation about the X-axis making an angle of -59° with respect to the Z-axis.

Figure (12) shows the echo pattern observed for the BC-cut crystal at 1.15 kMc/s and room temperature. The velocity measured was 5.03×10^5 cm/sec. A measurement of attenuation for these conditions gave a figure of about 1.4 db/cm. The A-C quartz rod was measured under the same conditions. Figure (13) shows the echo pattern. The pattern is not clear since there appears to be other modes being generated. The transverse velocities for this particular crystal are very close, being 3.84 and 3.32×10^5 cm/sec. The attenuation appears to be significantly larger for this cut of crystal compared to the BC cut rod.

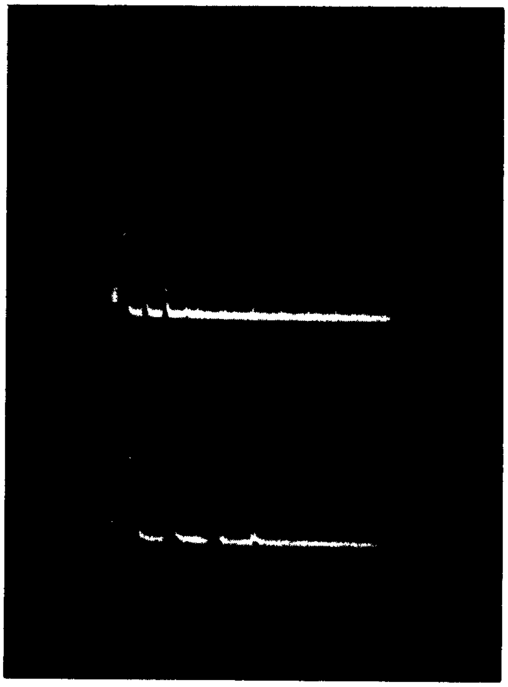


Figure 12. Transverse Wave Echo Pattern in B.C. Quartz, Magnetostrictive Excitation 1.15 kMc/s, Room Temperature

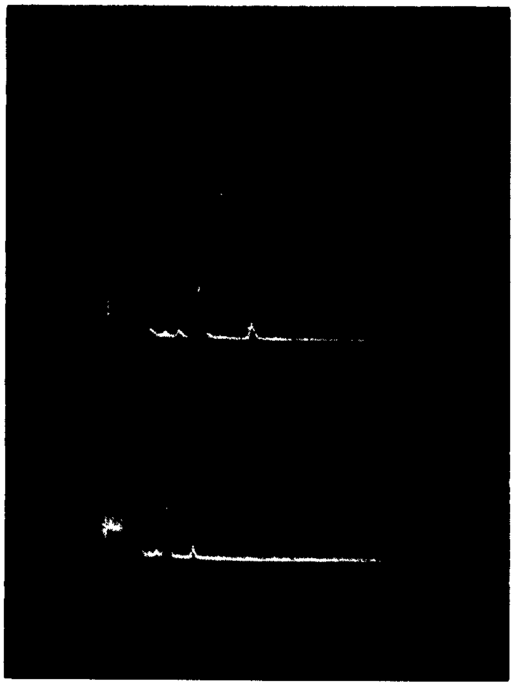


Figure 13. Echo Pattern in AC Quartz Magnetostrictive Excitation 1.15 kMc/s, Room Temperature

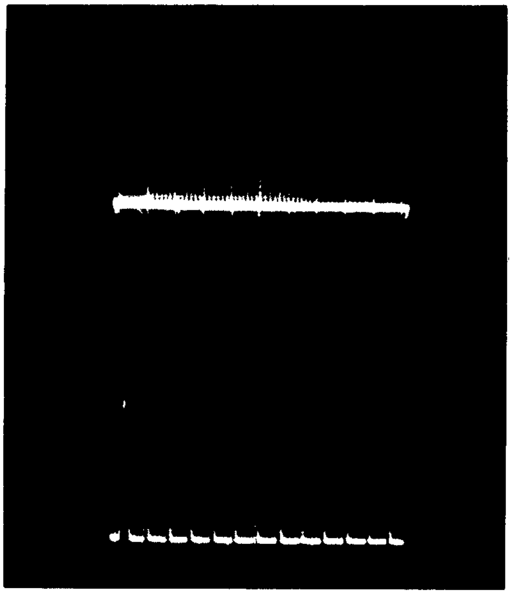
4.6.3 Phonon Propagation in Non-Piezoelectric Media

Microwave phonon propagation at 2.8 kMc/s was observed in silicon and germanium using thin quartz bonded transducers. This type of transducer and bonding is not ideally suitable at these frequencies and most of the generating techniques involved magnetostrictive transducers. The results of phonon propagation in the rest of this section has been accomplished using thin film magnetostrictive transducers.

Figure (14) shows the transverse mode echo pattern observed in <111> silicon. The characteristics of the material are as follows: p type, resistivity 5,000 ohm - cm. and carrier concentration 5×10^{12} atoms/cm^3. The test was carried out at liquid helium temperature and a frequency of 2.67 kMc/s. The velocity measured was 9.6×10^5 cm/sec. Figure (15) shows the transverse mode in <100> Ge. The material was n type, resistivity 55 ohm-cm. and carrier concentration of 1×10^{13} atoms/cm^3.

Phonon propagation has also been observed in other materials such as C-axis ruby, C-axis CdS, and <110> Ga As by these methods.

The electromechanical coupling coefficient of these types of magnetostrictive films has been reported as high as 40%. Measurements of insertion loss have been made using piezoelectric excitation and thin magnetostrictive films. For the piezoelectric case the insertion loss measured was about 90 db in and out. The insertion loss using magnetostrictive films was of the order of 75-80 db. in and out. Both measurements were made using a microwave cavity resonant at 1.15 kMc/s and at room temperature.



20 usec/cm.

10 usec/cm.

Figure 14. Magnetostrictive Excitation of Transverse Phonons in <111> Silicon

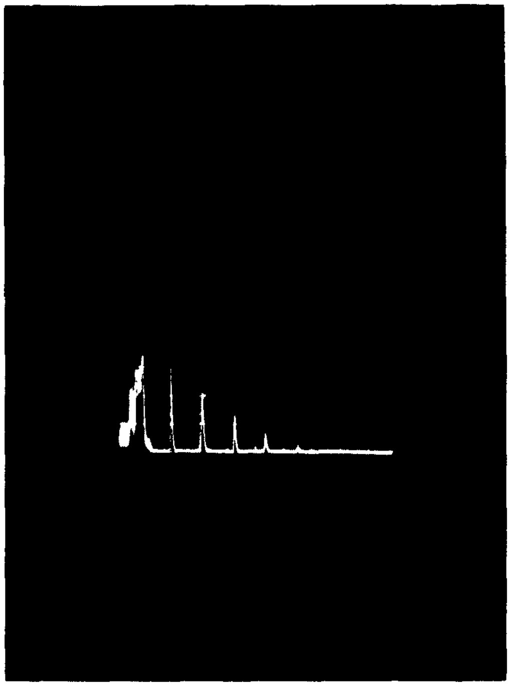


Figure 15. Magnetostrictive Excitation of Transverse Phonons in <100> Germanium

4.6.4 Phonon Propagation at Lower Frequencies

Although phonon-phonon interaction may still necessitate cooling the medium to cryogenic temperatures, useful data has been acquired and experimental procedures have been refined at room temperatures. Sound attenuation is reduced at frequencies below the kMc/s range. Phonon interaction testing at lower frequencies would still offer much useful information. Thin quartz transducers were applied to rods of quartz, CdS and KDP. Pulse echoes were observed in these crystals in the 5 to 30 Mc/s frequency region at room temperatures.

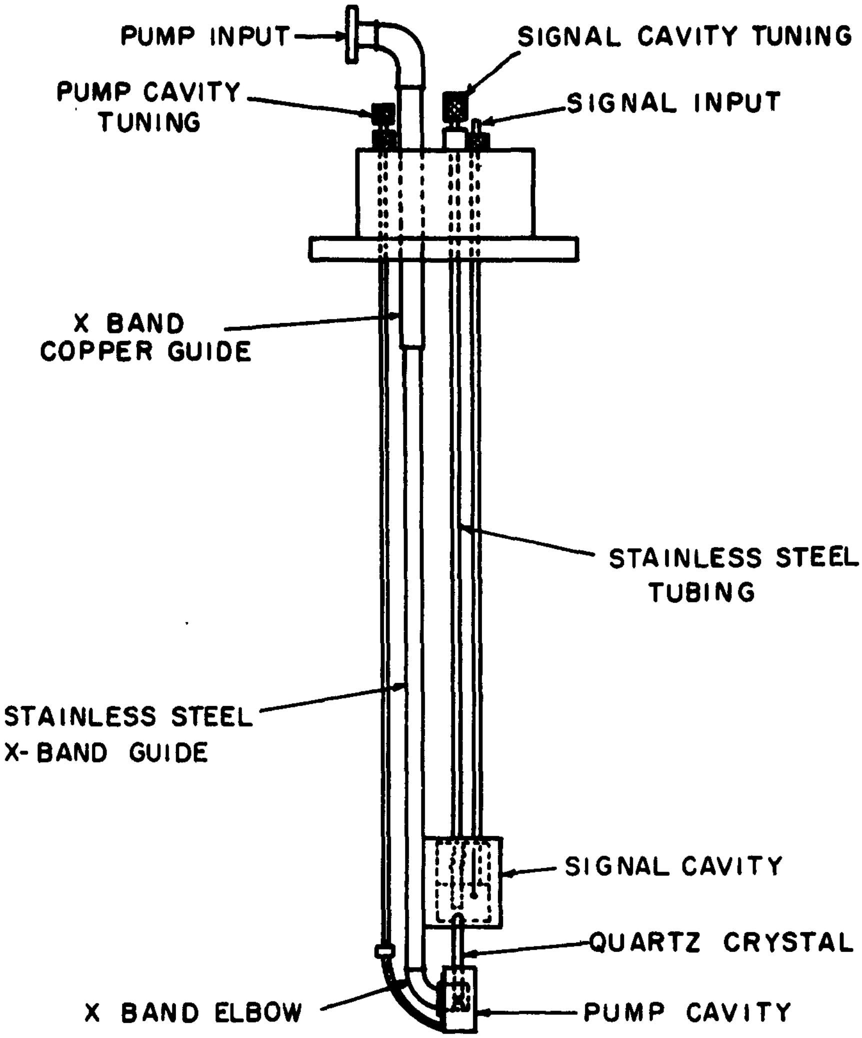
5. Phonon Interaction Experiments

5.1 Phonon-Phonon Interactions

The phonon-phonon interaction processes described in sections have been investigated in this study. A series of experiments were performed searching for evidence of phonon interactions in one of these various forms.

The backward wave interaction test included search of direct interaction yielding gain at the signal frequency. Quartz was one of the materials used with this experiment. Frequency ratios based upon calculations from the selection rules were used for determining the mode of operation. Tests were carried out at S-band signal and X-band pump frequencies. One end of the crystal was inserted in a tunable X-band microwave re-entrant cavity and the other end of the rod was placed in a tunable S-band microwave re-entrant cavity. Figure (16) shows a sketch of the apparatus. A CW magnetron rated at 50 watts average power was pulse modulated and used as the applied signal. An X-band magnetron rated at 50 KW peak power was used on the pump side. Echoes were observed at both frequencies while the pump and signal were being applied. No direct observation of interaction was obtained during this experiment. It is possible that the quartz may not possess a high enough degree of non-linearity since it is generally a high Q material. The experiment was repeated using a longitudinal pump and transverse signal mode in an X-cut quartz rod. The same results were obtained.

Tests of the same type were also conducted using $\langle 111 \rangle$ silicon rods and magnetostrictive transducers for acoustic coupling. The tests were made using a signal frequency at L-band and a pump frequency at S-band.



ASSEMBLY FOR BACKWARD TRAVELING WAVE INTERACTION EQUIPMENT

FIGURE 16

The pump power was supplied by using wide pulse modulation of a 50 watt CW magnetron. The longitudinal mode coupling was used at both frequencies. As the pump power was applied, a decrease in the signal echoes was observed. This may suggest a possible upper sideband absorption phenomena indicating a parametric interaction of up conversion. This process could occur when the signal and pump are of the same mode. These conditions were present in this case. However, the possibility exists that the decrease in echoes may have been due to internal thermal heating effects of the crystal when the pump power was applied. The decrease in echoes appeared to vary for different operating temperatures.

Experiments were then continued in an attempt to observe upper sideband frequency conversion using $\langle 111 \rangle$ silicon as the interacting medium. The frequencies involved are:

$$W_p = 3.35 \text{ kMc/s}$$

$$W_s = 1.1 \text{ kMc/s}$$

$$W_s + W_p = 4.45 \text{ kMc/s}$$

Pulse echoes were observed at both the pump and signal frequencies. No upper sideband frequency was observed. A C-band mixer preamp with a sensitivity of approximately (85-90 dbm, $\approx 10^{-12}$ watts) was used as the detection system in searching for the upper sideband. The pump power applied was about 5 KW peak and the signal power about 2 watts peak. The number of pump frequency echoes was of the order of about 30. This was probably due to lower efficiency of the magnetostrictive transducer. The transducer was used for generating the fundamental mode (1/4 wavelength) for the signal, and 3/4 wavelength for the pump. A magnetostrictive transducer operating on $\lambda/4$ mode was used on the other edge of the crystal for the upper sideband frequency.

Further tests were searching for harmonic generation and forward traveling wave type of interactions. Tests were made using an X-cut rod plated with magnetostrictive transducers on one end face. The rod was cooled to liquid helium temperature, pulses were generated at 3.3 kMc/s on the thin film edge using a pulsed magnetron rated at 5 KW peak power. A search was made for the third harmonic at 9.9 kMc/s using an X-band cavity. No third harmonic was observed.

Tests were performed on a silicon rod cut along the <111> axis. In these experiments one end of the rod was filmed so that it would operate at one kMc/s and the other filmed for three kMc/s. Both experiments seeking third harmonic generation of the 1 kMc/s signal and interaction between a 1 kMc/s and a 3 kMc/s signal were performed. The sample was cooled in liquid helium. No third harmonic could be detected when the crystal was driven at 1 kMc/s.

In the second tests of these series, one kMc/s echoes were obtained by driving the appropriate cavity, and a 3 kMc/s pump signal was applied to the other cavity. The time lapse between the pulses could be controlled so that the pump signal was applied just as the signal pulse was being reflected from the end of the sample being driven at the pump frequency. When this adjustment was made, a very slight decrease in the amplitude of the signal echoes was observed. This could be due to a direct feed-through from pump transmitter to signal receiver.

A similar test was performed on a <100> germanium crystal, using a magnetostrictive film transducer. The crystal was cooled in liquid helium, and the filmed end placed in a cavity that could be excited both at 1.1 kMc/s and 3.3 kMc/s, by using a 1/4 and 3/4 wavelength mode respectively. Both longitudinal echoes, with a velocity of 5×10^5 cm/sec. and transverse echoes with a velocity of 3.56×10^5 cm/sec. could be observed at both frequencies.

The sample was excited simultaneously with 1.1 and 3.3 kMc/s energy. The 1.1 kMc/s echoes were observed to show a slight gain in amplitude when the 3.3 kMc/s signal was applied. However, this was definitely proved to be RF feed-through from the S-band transmitter to the L-band receiver.

Crystals of CdS and KDP were also prepared for phonon interaction testing in the 5 to 30 Mc frequency range. Pulse echoes were observed in both rods at these frequencies, but no appreciable phonon interaction testing was made of these samples.

5.2 Experimental Aspects of Optically Pumped Phonon Maser Interactions

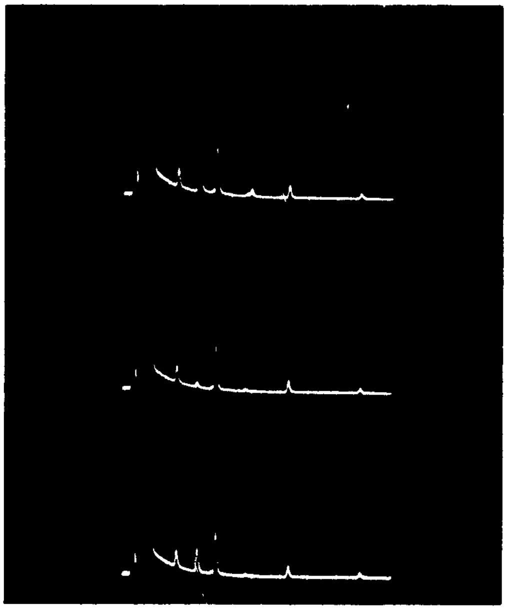
The feasibility of amplifying phonons in ruby by means of optically pumped phonon maser interactions was discussed in section 4.3. This technique could possibly offer a more sensitive means of detection. A preliminary step to studying the amplification of phonons in ruby by means of optically pumped phonon interaction would involve the observation of microwave generation by stimulated emission at liquid nitrogen temperature. A structure used in maser studies was modified for such a purpose. A microwave assembly consisting of an X-band waveguide terminated by a cylindrical cavity resonant in the fundamental TE 101 mode was prepared for the experimental study. The cavity is resonant at X-band frequency and is loaded with a piece of ruby. A long quartz pipe is supported along the edge of the waveguide. Prisms are attached to both ends of the rod; one at the top, external to the structure and the other at the bottom. The lower prism directs the laser light to the ruby via a small hole in the cylindrical wall of the cavity. The whole microwave structure is placed in a liquid nitrogen dewar that is fitted between the pole pieces of a Varian electromagnet. A ruby laser operating at liquid nitrogen temperature was designed for use in these experimental studies. Laser radiation from the liquid nitrogen cooled ruby laser is beamed to the external prism, channeled down the quartz pipe, then through the bottom prism and into the ruby. A low microwave signal is applied and the required conditions of field strength and orientation for maser transitions between the various levels are then set. Oscillations or amplification of the microwave signal are then searched for when the optical laser illuminates the maser crystal. Once this has been achieved, the set up would be modified to include a means of generating microwave phonons at the desired frequency. This experiment was delayed in order to concentrate efforts on the phonon-phonon interactions testing.

5.3 Electron Phonon Interaction in GaAs

Gallium arsenide is a material being used in our phonon interaction studies. Since phonon propagation was observed in this material (see 4th quarterly progress report) a few tests were made for studying electron-phonon interaction at 1.15 kMc/s. and liquid helium temperature. The experiment was performed using a bar shaped single GaAs crystal .150" x 158" x .665" in size. The crystalline axis was oriented in a <110> direction. For propagation in this direction only the fast transverse wave is piezoelectrically coupled. It is this transverse mode (vel. = 3.35×10^5 cm/sec.) that exhibits the observed electron-phonon interaction.

The crystal was filmed with a magnetostrictive transducer for generating the phonon wave. Electrical leads for biasing were soldered to the films on the small end faces of the crystal. The crystal was then inserted in a microwave re-entrant type cavity resonant at 1.15 kMc/s and the unit was cooled to liquid helium temperature.

Figure (17) shows the pulse echo pattern observed. Two echoes of the fast transverse mode are visible at the 3 and 5 cm. line marking of the oscilloscope. Light from a microscopic lamp was directed onto the crystal and the fast transverse pulses reduced in magnitude. The first pulse is still visible while the second pulse has been completely attenuated. A d.c. voltage was then applied to the crystal. At approximately 110 volts bias, some interaction was distinctly visible. The first pulse was gaining in amplitude. The gain, however, was not yet large enough to overcome the absorption due to optically excited carriers. An increase in d.c. voltage produced arcing with the present experimental arrangement.



Pulses at 3rd and 5th cm. line marking are of the fast transverse mode. Time scale is 10 usec/cm.

Microscope light intensity is applied. Echoes reduce very rapidly.

110 volts d.c. bias applied Echo reappears to height about 1/3 of its original magnitude.

Figure 17

Electron Phonon Interaction In GaAs

Crystal	⟨110⟩ GaAs 1.140" x .158" x .665"
Frequency	1.15 kMc/s
Transducer	Magnetostrictive films
Temperature	Liquid helium
Mode	Transverse 3.56×10^5 cm/sec.
Delay	9.5 usec. for round trip

6. CONCLUSION

Various interaction processes have been investigated for parametric interaction of phonons. These included forward and backward traveling wave types of interactions with a search for gain in the signal amplitude. Harmonic generation and frequency up conversion were also investigated.

The forward type of traveling wave interaction showed a decrease in the signal echo amplitude when the pump power was applied. The effect may be due to thermal heating of the interaction medium or possibly upper sideband absorption of sum frequency power. Experiments involving frequency up conversion did not show any conclusive evidence, of this process, since no sum frequency power was observed. The level of the sum frequency power may possibly have been extremely low and no signal at this frequency was detected. The level of the pump acoustic power may be too low to drive the crystal to a high degree of non-linearity. The basic problem in this respect is that transducer efficiency is still quite low in the present state of the art. A more efficient transducer is, therefore, highly desirable for coupling more acoustic energy into the medium. On the other hand the crystals used may not exhibit a high enough figure of non-linearity. However, it is believed that a necessary approach would be to obtain more effieient means of transduction. More conclusive data would result during experimental testing of this type.

The upper sideband frequency conversion experiment appears to be most likely to succeed. This type of interaction simplified the experimental procedure since it involves creation of a single phonon and in this respect seems more probable than the multi-phonon processes involved in the forward and backward wave type of interaction.

Tests involving harmonic generation could be useful for studying the degree of non-linearity in various crystals. These experiments would necessitate investigation to determine whether the harmonic generation was due to surface or volume effects.

The electron-phonon and spin phonon interactions could be useful as detection means. Both have been already verified experimentally and either could be used to generate large amplitude sound and to detect weak ultrasonic waves.

From the practical viewpoint, the interpretation of parametric interactions leads to new ways of detecting phonon interactions in solids, as well as new devices in the form of phonon detectors or amplifiers. An example of device application is an ultrasonic amplifier in which the inherent high losses are overcome by amplification. From a purely scientific viewpoint, generation and interaction of coherent phonon waves offers a key for better understanding of transport phenomena in solids.

7. IDENTIFICATION OF PERSONNEL

Dr. Hsuing Hsu	959 hours
Dr. Walter Brouillette	188 hours
Stephen Wanuga	3035 hours

8. ABSTRACT CARDS

AD

General Electric Co., Syracuse, N. Y.
PHONON-PHONON INTERACTION IN CRYSTALS by Hsiung Hsu and Stephen Wanuga. First Quarterly Progress Report 1 May 1961-31 July 1961. 61 p. incl. line drawings and photographs. (Contract DA-36-039-sc-87209)
Unclassified Report

The objective of this project is to study the generation, propagation, and interaction of phonons in solids by means of microwaves with emphasis on the phonon-phonon interaction in crystals. These phonon interactions are interpreted as parametric interactions due to crystal anharmonicity.

In this quarterly report, the concept of three dimensional parametric interactions is discussed. The mechanism of various types of traveling wave parametric interactions are analyzed. The selection rules of coupled phonon modes and various experimental approaches are described. Detailed discussions on the low temperature microwave structures and experimental results on the generation and propagation of microwave phonons are presented.

UNCLASSIFIED

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2. Phonon-Phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

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1. Generation and propagation of hypersonic phonons
2. Phonon-phonon Interaction
3. Parametric Interaction

I. Hsu, Hsiung
II. Wanuga, Stephen
III. Contract DA-36-039-sc-87209

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